UCRL-JC-119070
PREPRINT

The HYLIFE-II Inertial Fusion Energy Power Plant Concept and Implications for IFE

Ralph W. Moir

This paper was prepared for submittal to the
American Physical Society
Division of Plasma Physics
36th Annual Meeting
Minneapolis, NM
November 7-11, 1994

November 1994

Lawrence Livermore National Laboratory

The HYLIFE-II Inertial Fusion Energy Power Plant Concept and Implications for IFE

Ralph W. Moir

HYLIFE-II is based on nonflammable, renewable-liquid-wall fusion target chambers formed with Li_2BeF_4 molten-salt jets, a heavy-ion driver, and single-sided illumination of indirect-drive targets. Building fusion chambers from existing materials with life-of-plant structural walls behind the liquid walls, while still meeting non-nuclear grade construction and low-level waste requirements, has profound implications for IFE development. Fluid-flow work and computational fluid dynamics predict chamber clearing adequate for 6-Hz pulse rates. Predicted electricity cost is reduced about 30% to 4.4¢/kWh at 1 GWe. Development can be foreshortened and cost reduced by obviating expensive neutron sources to develop first-wall materials. The driver and chamber can be upgraded in stages, avoiding separate and sequential facilities. The most important features of a practical inertial fusion power plant are sufficient ignition and gain in targets; a low-cost, efficient, rep-ratable driver; and low-cost targets.

I. INTRODUCTION

Among the many problems faced en route to practical fusion is how to cope with the highly energetic 14-MeV neutrons that are expected to seriously damage the first-wall materials. The idea examined here is to use a liquid wall facing the fusion region, thick enough to slow down and stop most of the neutrons before they damage the solid structural material behind the liquid layer. Using a thick liquid wall offers a number of profound benefits that have not been adequately appreciated and that may both ease fusion energy development and make the end product so much more desirable as to speed up its development. As discussed later, these benefits are generic to any liquid-wall fusion energy concept, either magnetic (MFE) or inertial (IFE), but because of inherent differences, the practical implementation of liquid walls is not the same for MFE and IFE.

II. LIQUID PROTECTION RESULTS IN LIFE-OF-PLANT STRUCTURES

The lifetime of structural steel has been calculated[1] (and plotted in Fig. 1) for a simplified geometry of a point neutron source and a shell of varying thickness for two lithium-containing liquids with low vapor pressure at temperatures of interest to thermal power conversion systems. These two liquids are Flibe (a molten salt, Li_2BeF_4) and lithium. For a thickness of 0.5 m of Flibe or 1.6 m of lithium, the structural material will last for 30 years before its structural properties are seriously degraded. A third liquid, a mixture of lithium and lead, also has sufficient lithium content to be considered for fusion (i.e., neutrons reacting with Li produce the fusion fuel, tritium).

III. LOW ACTIVATION QUALIFIES FOR SHALLOW BURIAL UPON DECOMMISSIONING

One way to determine how much activation of structures in a nuclear system can be permitted is to assume the material would qualify for shallow land burial. The shallow burial requirement applies the concept of the “intruder dose.” The burial site is assumed to be guarded for 100 years. After 500 years, intruders are assumed to dig up the site and live their whole lives there. A person standing next to a large block of waste material would receive what is called the *whole-life* (70-year) *intruder dose*. This is to be compared to the “acceptable” lifetime dose of radiation, 5 mSv/y (0.5 rem/y), typical of the background dose from natural sources.[2] This intruder dose has been calculated[3] for various thicknesses of liquid. Figure 2 shows that 304 stainless steel protected by a Flibe layer thicker than 0.8 m would result in an adequately low intruder dose and thus would qualify for shallow land burial upon decommissioning.

IV. HYLIFE-II IS AN INERTIAL FUSION POWER PLANT DESIGN PROTECTED BY A LIQUID WALL

HYLIFE-II is an inertial fusion power plant design concept[1] that uses a thick liquid wall. Figures 3, 4, and 5 show several views of HYLIFE-II. Heavy-ion beams are focused on a target[7] from one side to initiate microexplosions six times per second. The yield is 350 MJ, or 100,000 times smaller than the earliest fission bombs. The liquid cushions the shock and blast effects to easily manageable levels and slows and captures the neutrons so that the solid materials are predicted to last the life of the plant. In this example, only about 0.2% of the source neutrons escape up the heavy-ion beam ports. A liquid accurately injected close to the target (inside the dashed region shown in Fig. 5b) may attenuate, by two orders of magnitude, even those (0.2%) neutrons, while still allowing the beams to strike the proper place on the target. (Reference 2 discusses this idea, along with a modified beam array of two columns of six beams each.) Careful design probably could reduce the damage and activation caused by these neutrons enough so that the cited advantages would be realized. The flowing liquid both carries the heat produced to the power plant, where it is converted into electricity, and clears the chamber for the next shot 1/6 of a second later.

The dramatically higher wall loading illustrates the effectiveness of liquid wall protection. For the HYLIFE-II example with a wall at 3 m, the power flux carried by fusion’s energetic 14-MeV neutrons toward the wall is 15 MW/m^2. Although this is a factor of 5 higher than the 3 MW/m^2 in some tokamak magnetic fusion designs, the liquid strongly attenuates these neutrons.

If the liquid is thick enough, structural damage can be reduced enough so that the structures will last the life of the plant. In fusion concepts with solid first walls, plants would have to shut down every few years for replacing the damaged blanket structures surrounding the fusion reaction. Not having to shut down would increase the plant capacity factor, perhaps from 75% to 85%, with a corresponding 12% reduction in the cost of electricity (COE).[1]

In addition, highly radioactive blanket structures need special handling machines and special storage rooms to prepare them for transportation to a disposal site. By contrast, a thick liquid wall would reduce the damage so much that the materials would last the life of the plant and would thus require removal only upon decommissioning. The savings that would result from fewer blanket structures over the life of the plant and less handling equipment, storage space, and waste disposal would be considerable, with an estimated[1] additional 12% reduction in the COE.

Many of the components, including parts of the tritium system, can be of the lower-cost, non-nuclear grade because failure of those components in an accident would not affect the public. Thus, the combined savings of higher plant capacity factor and no blanket structures being replaced during the life of the plant, plus other improvements discussed in Ref. 4, would result in a 35% lower COE.

Another advantage of reduced activation would be that the consequence of any accident or abnormal event might be so much less that no harm would be suffered by the public even if stainless steel were used instead of exotic materials such as silicon carbide or vanadium. Therefore, ordinary industrial-grade construction standards could be used rather than the much more rigorous and expensive nuclear-grade (the so-called “N-Stamp” certification) construction standard. With liquid protection, ordinary 304 stainless steel is predicted to qualify, eliminating the need for new materials. This would reduce costs and improve the public’s perception of fusion power by reassuring the public that, even in the event of an accident, nobody beyond the site boundary would be harmed.

V. LIQUID-WALL FUSION CONCEPT APPLIES TO MAGNETIC FUSION

In 1970, N. C. Christofilos[5] (published posthumously in 1989) suggested a liquid-walled concept for magnetic fusion. In magnetic fusion, the liquid can contaminate the fusion plasma, cooling it below the fusion temperature. The vapor pressure (density) then becomes an important parameter in choosing the liquid and its operating temperature. The three liquids mentioned here have rather low vapor pressures (densities below $10^{13}/cm^3$) at temperatures of interest to thermal power-conversion systems. However, in inertial fusion, fusion reactions are over when the pulse of evaporated material arrives, and the interpulse time is sufficient to condense the vapor produced by the microexplosion. Reference 2 presents other magnetic fusion configurations in which liquid protection has been discussed.

VI. RESEARCH AND DEVELOPMENT IS NEEDED TO RESOLVE CONCERNS UNIQUE TO LIQUID-WALL FUSION CONCEPTS

There are some concerns unique to liquid-walled fusion concepts that need research and development to resolve:

- The evaporated liquid must condense quickly enough to avoid limiting the pulse rate in inertial fusion by interfering with the passage of the beams to the target.
- The splashed liquid from a prior microexplosion must not interfere with the passage of the beams to the target (in magnetic fusion, splashed liquid could

contaminate the plasma), and it remains to be demonstrated by experiment that liquid configurations can be created repeatedly with sufficiently little splash.

• The moving parts that create the liquid configuration must not degrade the advantages of using liquid protection. (The amount of liquid required and the pumping power can become significant. In the example of Ref. 1, the cost of the liquid and its pumping power contribute about 9% of the COE, a substantial but acceptable amount, considering that considerable pumping and heat-transfer liquid are needed in any fusion power plant.)

It remains to be shown by laboratory demonstrations that liquid configurations can be made to meet these conditions and thereby achieve the stated advantages.

VII. A LIQUID FIRST WALL ELIMINATES THE NEED FOR INTENSE AND VOLUMETRIC NEUTRON SOURCES

Eliminating the need for a first wall would also eliminate the need for an expensive program to develop first-wall materials. Constructing neutron sources likely would cost more than $1 billion each. According to some claims, development of first-wall materials for fusion might cost many billions of dollars and take decades, making it as expensive and as lengthy as development of the controlled fusion reaction itself. The use of a thick liquid wall is predicted largely to do away with this first-wall problem. The 14-MeV neutrons impinging on the liquid are attenuated and their spectra are softened enough that testing can be carried out in fission reactors. The remaining question will have to do with the effects of the pulsed nature (i.e., rate effects) of the neutrons in inertial fusion energy.

VIII. LOW-COST DEVELOPMENT SCENARIO FOR IFE

The cost and time of development would be reduced by using an engineering test facility (ETF) with a driver and a chamber that can be upgraded. Based on past experience in high-energy accelerator facilities, a heavy-ion accelerator should be capable of being upgraded by using modular components. Focusing can be tested at the 100-kJ level at ~100 MeV with the “front end” of the ETF driver as a first stage. Beam energy (up to 5 MJ) can be increased along with ion energy (up to 10 GeV) by adding modular accelerator stages—the number of which would be determined by minimum ignition and gain requirements established by the proposed National Ignition Facility (NIF) and theory.

To expedite testing and selection of IFE chamber technology options, a heavy ion beam can be switched by magnets to drive multiple target chambers. Once the ETF identifies a suitable chamber concept for a power plant, through low-power testing, the ETF facility can be upgraded to a demonstration plant using a new, full-sized chamber and an upgraded driver (scaled up in beam energy, ion energy and rep rate). (The cost of a heavy-ion drive is a weak function of drive energy and even less of rep rate.) A recent study[6] shows that the fusion-chamber technology issues for most IFE chambers options can be tested at reduced scale and reduced average fusion power.

IX. REQUIREMENTS FOR IFE BEYOND THOSE SPECIFIC TO LIQUID-WALL PROTECTION

HYLIFE-II, like other IFE concepts, requires sufficiently good physics performance from targets such that they ignite and obtain a gain of about 70. For 5 MJ, this is predicted to be obtainable by using a heavy-ion beam with a 2-mm-radius focal spot. The driver must be reliable and deliver the beam in a 2-mm-radius spot 6 times per second. If the spot size turns out to have a 4-mm radius instead, the COE is predicted to increase by about 12% and the gain to drop to 47. The direct cost of the heavy-ion driver, predicted to be ~$600 million for 1000 MWe, comprises 38% of the total cost of the plant. If the driver cost increases to $1.2 billion, the COE would increase 38% from its predicted value of 4.4¢/kWh at 1 GWe. A similar increase at 2 GWe would increase the COE by 27%. The target factory is predicted to have a direct cost of $60 million and a $12 million/y operating cost. This results in a cost per target of 14¢ and amounts to 7% of the COE.

X. PROFOUND IMPLICATIONS OF LIQUID PROTECTION FOR IFE DEVELOPMENT

The advantages stated here can be described as having five profound implications for development of inertial fusion energy:

- Life-of-plant structures mean
  –no periodic downtime for first-wall/blanket replacement; COE reduced 12%.
  –no replacement costs for new first wall/blankets, equipment, and hot cells; COE reduced 12%.
- No need to develop new materials; 304 SS qualifies for shallow burial at decommission time (low-activation material).
- High fluence and volumetric neutron source not needed to develop first-wall materials.
- Cost of electricity is lower than for fission and fossil fuels.
- Development cost and time can be reduced for IFE by upgrading the driver and chamber in stages from an engineering test facility to a demonstration power plant.

Experiments are needed to put the concept of liquid-wall protection on a firm foundation. Reseach and development on liquid-jet formation, chamber clearing, condensation, and reliability of moving jets are called for.

XI. SUMMARY

In summary, the concept of a thick liquid surrounding the fusion reaction chamber offers advantages to inertial fusion that could lower its cost of electricity more than 30%, lower its development cost by billions of dollars by easing the materials-development problem, and further increase the environmental and safety advantages of fusion. Upgrading the driver and chamber in stages in an engineering test facility to a demonstration power plant can further shorten development time and reduce its cost. With these promised advantages that could have such a profound impact on fusion’s development, there is considerable incentive to invest research funds into the liquid-wall concept to see if the claims are as advantageous as they appear.

ACKNOWLEDGMENTS

Discussions with Grant Logan are gratefully acknowledged. This work was performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under Contract No. W-7405-Eng-48.

REFERENCES

[1] R. W. Moir, R. L. Bieri, X. M. Chen, T. J. Dolan, M. A. Hoffman, P. A. House, R. L. Leber, J. D. Lee, Y. T. Lee, J. C. Liu, G. R. Longhurst, W. R. Meier, P. F. Peterson, R. W. Petzoldt, V. E. Schrock, M. T. Tobin, and W. H. Williams, Fusion Technol. **25**, 5 (1994).

[2] R. W. Moir, “The Logic Behind Thick, Liquid-Walled, Fusion Concepts,” in Proc. Third Int. Symp. on Fusion Nucl. Technol. June 27–July 1, 1994, University of California, Los Angeles, California, to appear in Fusion Eng. Design.

[3] J. D. Lee, Fusion Technol. **26**, 74 (1994).

[4] R. W. Moir. “Improvements to the HYLIFE-II Inertial Fusion Energy Power Plant Design,” in Proc. 11th Topical Meeting on Technol. of Fusion Energy, June 19–23, 1994, New Orleans, Louisiana, to appear in Fusion Technol.

[5] N. C. Christofilos, J. Fusion Energy **8**, 97 (1989).

[6] W. J. Hogan and W. R. Meier, Nuovo Cimento **106A**(12), 1971 (1993).

[7] D. D–M. Ho, J. A. Harte, and M. Tabak, “Target Physics for Heavy Ion Fusion,” to appear in Nucl. Fusion Suppl.

Figures

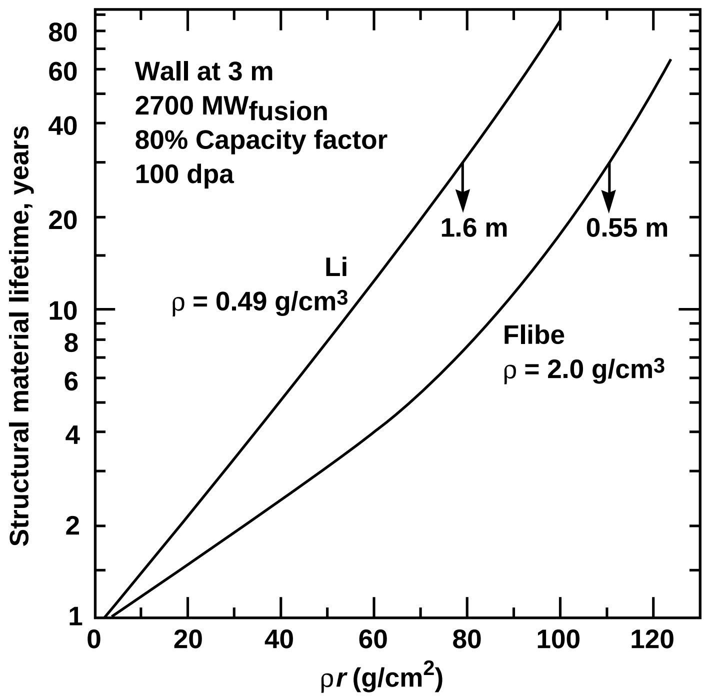

Figure 1. Structural material lifetime vs thickness of the liquid protecting the structural material. The lifetime is measured by the term that materials people call "displacements per atom," taken as 100 for austenitic steels such as 304 stainless steel.

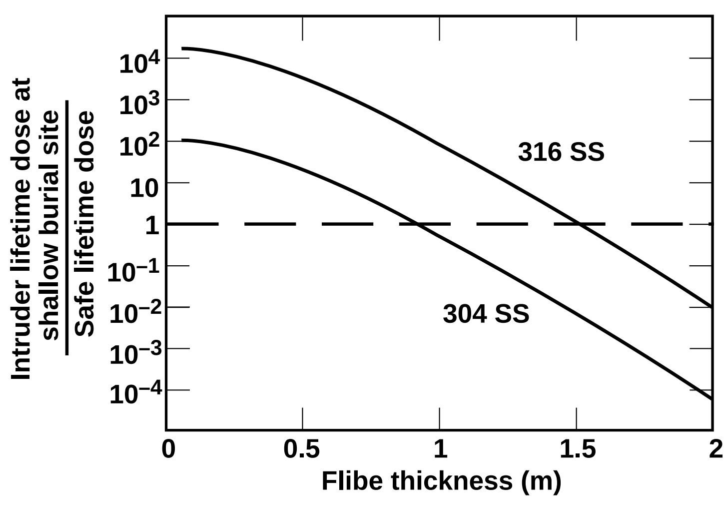

Figure 2. Intruder lifetime dose vs thickness of the liquid protecting the structural material normalized to the "safe" dose of 5 mSv/y or 0.5 rem/y. If the normalized intruder dose is less than unity, the material qualifies for shallow land burial.

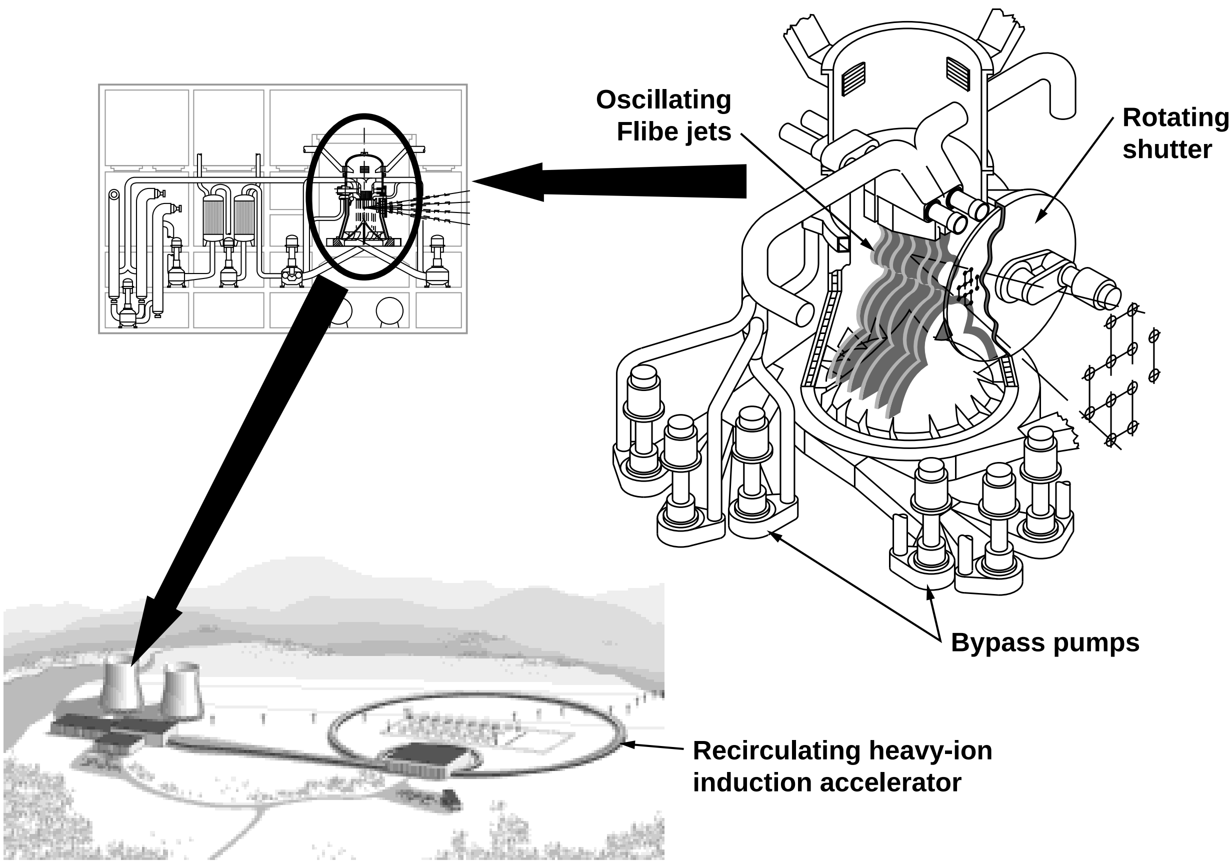

Figure 3. A heavy-ion induction accelerator illuminates targets from one side. Pumps circulate liquid Flibe (Li_2BeF_4) to protect the walls of the reaction chamber.

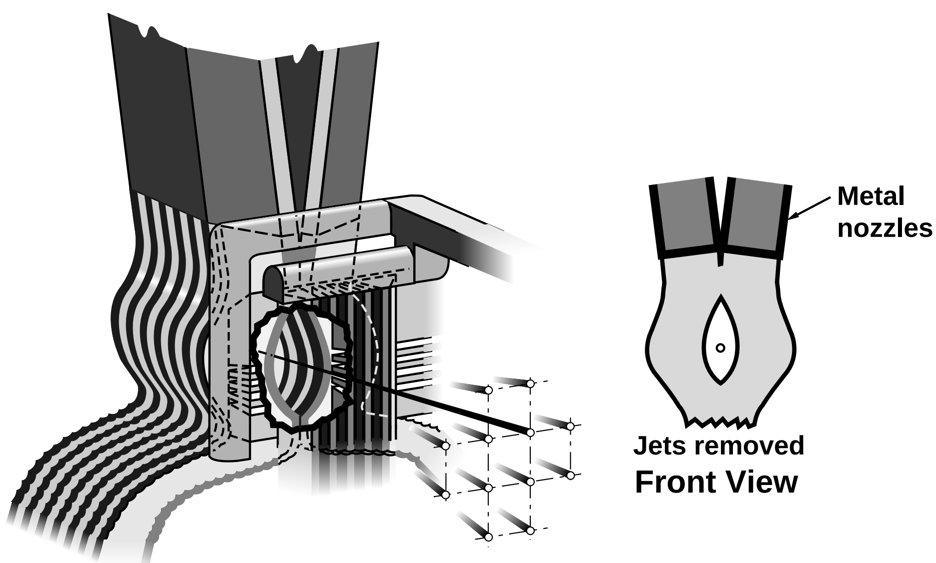

Figure 4. Artist's view of the liquid configuration that protects the chamber structure, showing the set of crossed jets of liquid that protect the beam port and the liquid that forms a pocket around the microexplosion. The front view, with the crossed jets of liquid removed, shows the liquid pocket.

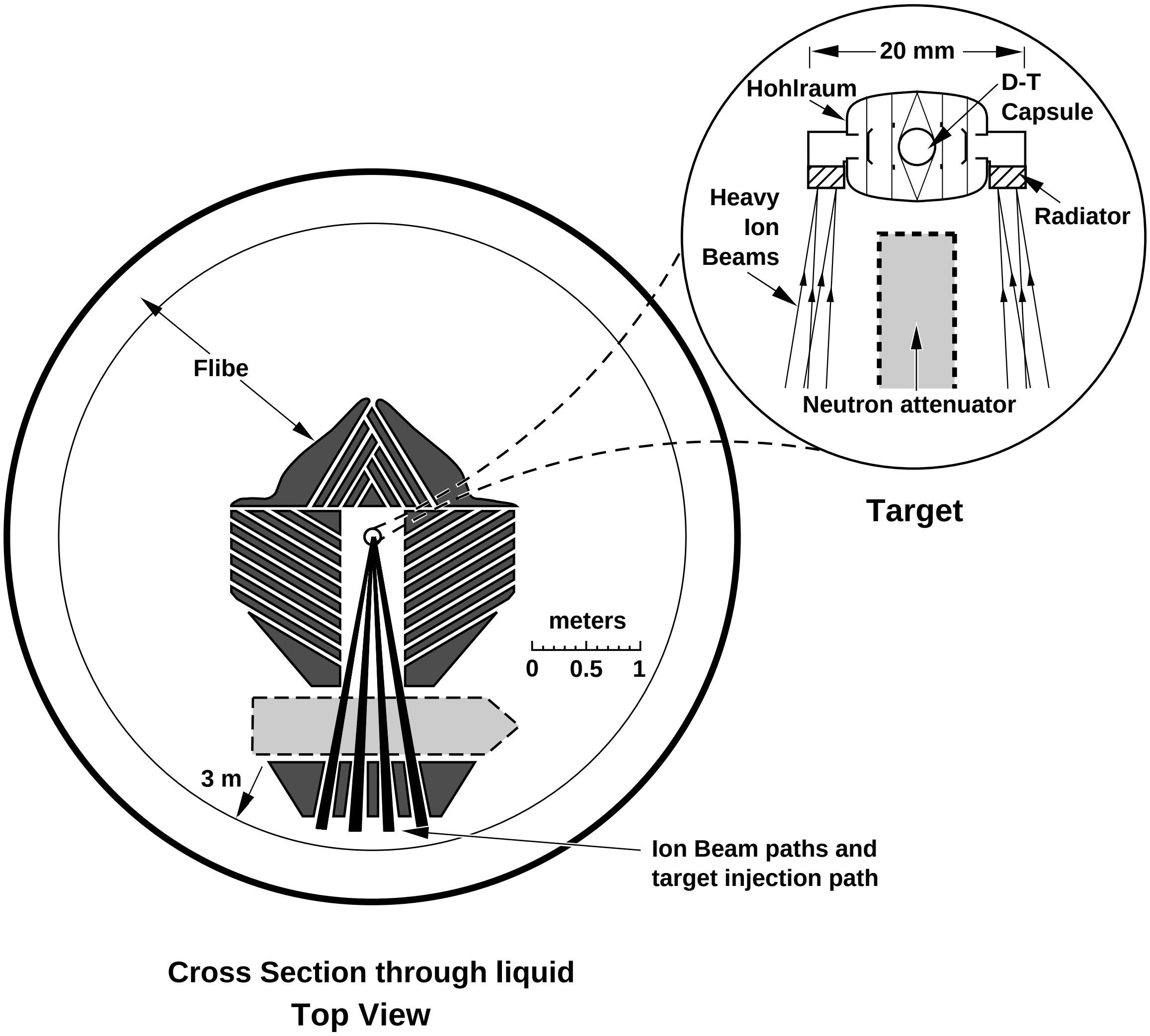

Figure 5. Cross section of the chamber at the target elevation: (a) top view, showing the open space for vapor venting and 0.5 m of liquid to attenuate neutrons in all directions except the beam paths; (b) the heavy-ion target. The single-sided illumination reduces cost of final beam transport and aids beam port protection.

Technical Information Department • Lawrence Livermore National Laboratory
University of California • Livermore, California 94551